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DOI:

[10.1109/EuCAP.2016.7481551](https://doi.org/10.1109/EuCAP.2016.7481551)

Document Version

Peer reviewed version

Citation for published version (Harvard):

Pacheco-Peña, V, Navarro-Cia, M, Orazbayev, B, Minin, IV, Minin, OV & Beruete, M 2016, Improving the performance of the zoned fishnet metalens using the reference phase technique. in *2016 10th European Conference on Antennas and Propagation (EuCAP)*. Institute of Electrical and Electronics Engineers (IEEE). <https://doi.org/10.1109/EuCAP.2016.7481551>

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Improving the Performance of the Zoned Fishnet Metalens Using the Reference Phase Technique

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Abstract—The reference phase, first proposed for the design of Fresnel Zoned Plates Antennas with reduced side-lobe levels, is applied here in the design of zoned fishnet metamaterial lenses. Four different metalens designs at $f=56.7$ GHz are presented with values of reference phase of 0 , 0.7π , 1.4π and 2π . Numerical results demonstrate that the best focusing performance is obtained for the metalens design of 0.7π in terms of the focal length, power at the focal length, side lobe level and first null. This performance is experimentally validated by comparing the focusing properties of metalenses with (0.7π) and without reference phase (0). Experimental results demonstrate a good agreement with numerical ones with a reduction of side lobes of 2.5dB and first null of ~ 12 dB for the design with reference phase.

Index Terms—Fishnet metamaterial, reference phase, zoned lens, Fresnel Zoned Plates.

I. INTRODUCTION

The Fresnel Zoned Plates Antennas (FZPA) have been extensively studied through years with the aim to improve the performance of communication systems [1]. The FZPA consists of a transmitter placed at the focal length (FL) of a Fresnel Zoned Plates Lens (FZPL). This type of lens has been studied and applied in the design of diffractive lenses for the whole frequency spectrum [2].

Refractive lenses designed with dielectrics or metals have been proposed and widely applied at microwave frequencies [3], [4]. Renewed attention into the design of refractive lenses has been put recently as a result of the introduction of metamaterials [5]–[10]. This is due to the arbitrary control of the electromagnetic parameters that metamaterials enable. Hence, these artificial materials permit to match the lenses with free space without using other techniques such as anti-reflective coats. Within the realm of metamaterials, the fishnet metamaterial with double in-plane periodicity has demonstrated to be a good candidate in the design of all metallic lenses (metalenses) [11], [12] since it filters the cross-polarization in addition to the providing impedance matching with free space [13]. Thus, several types of metalenses have been proposed and experimentally demonstrated, such as plano-concave and bi-concave profiled metalenses. Recently,

the zoned technique has been applied to them to reduce their volume. This technique relies on reducing the metalens' profile when the electromagnetic waves passing through them reach a redundant phase advance of 2π . It has been demonstrated that the fishnet metalens focusing performance (and the radiation pattern when they are used as a lens-antenna) is not deteriorated compared with the full profiled concave metalens [14]–[16].

The *reference phase* concept has been recently proposed and applied in the design of FZPA in order to reduce the side-lobe levels (SLL) of the lens when evaluating its focusing performance and also under the lens-antenna configuration [17]. For the case of refractive lenses (such as fishnet metalenses), this technique is based on the introduction of an extra phase between 0 and 2π to the central zone. As it can be deduced from this technique, the successive zones are affected due to this extra phase, increasing their thickness and also the total volume of the lens.

In this work, the reference phase technique is applied together with the zoning technique in the design of metalenses based on the fishnet metamaterial in order to reduce the side-lobe level and first null at the focal position [18]. First, the design of four lenses with discrete values of reference phase is shown (0 , 0.7π , 1.4π and 2π). Then, the focusing performance of these designs is evaluated numerically in more detail than in Ref. 18, demonstrating that the best performance is obtained for a reference phase of 0.7π with a SLL of 9.7 dB and first null of 17 dB. These results are validated experimentally evaluating the focusing performance of two metalenses with and without reference phase; corroborating that a reduction of SLL and first null can be achieved with this technique.

II. DESIGN AND NUMERICAL RESULTS

A. Applying reference phase to the zoning technique

As it has been explained in the introduction, for the zoned lenses the profile is reduced each time it reaches a thickness limit defined as $t = \lambda_0 / (1 - n_{lens})$, where λ_0 is the wavelength in vacuum and n_{lens} is the refractive index of the lens. This value of t is related to a phase advance of 2π of the electromagnetic

waves passing through the lens. Hence, the extra phase due to the reference phase can be introduced in the previous equation in terms of an extra thickness (Δt). Thus, the thickness limit for zoned lenses with reference phase is calculated as $t_{total} = t + \Delta t = \lambda_0 / (1 - n_{lens}) + q[\lambda_0 / (1 - n_{lens})]$ [18]. Here, q is a value between 0 and 1 and represents an extra phase of 0 and 2π , respectively. Based on this, we can use this thickness limit along with the general equation of a conical section in order to design the profiles of the fishnet metalenses, as follows:

$$(1 - n_{lens}^2)(z + mt)^2 - 2(FL + mt)(1 - n_{lens})(z + mt) + x^2 = 0 \quad (1)$$

where FL is the focal length and $m = 0, 1, 2, \dots$ corresponds to the non-zoned profile ($m = 0$) and the successive steps ($m > 0$).

B. Zoned Fishnet Metalenses: Numerical and experimental results.

The zoned fishnet metalenses here studied are designed using a unit cell with the same dimensions as in our previous studies [11], [14]–[16], [19]. A scheme is shown in the inset of Fig. 1(a) along with the numerically calculated refractive index using the commercial software CST Microwave StudioTM considering an infinite number of stacked plates along all directions. Note that due to the discrete value of the dimension along z (d_z), there is a limit of values of reference phase that can be used with this fishnet metamaterial. These values are $q = 0$, $q = 0.35$, $q = 0.7$ and $q = 1$ which correspond to a reference phase of 0, 0.7π , 1.4π and 2π , respectively.

All metalenses are designed at $f = 56.7$ GHz ($\lambda_0 = 5.29$ mm)

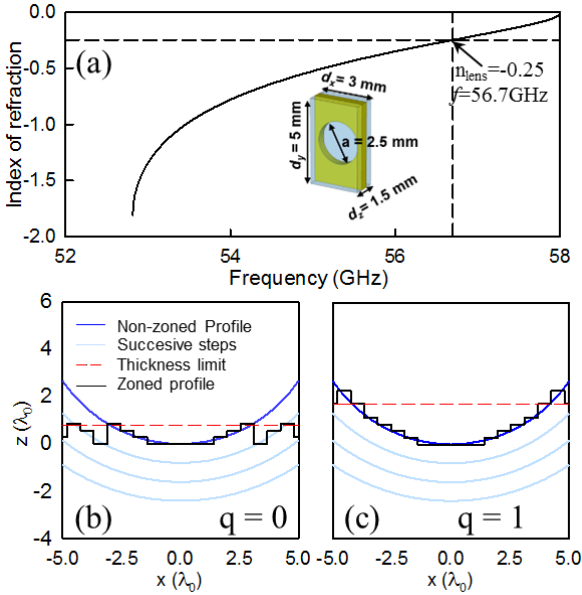


Fig.1 (a) Numerical results of the refractive index for the fishnet metamaterial here used in the design of the zoned metalenses. The dimensions of the unit cell are: $d_x = 3$ mm, $d_y = 5$ mm, metal thickness $w = 0.5$ mm, $d_z = 1.5$ mm and hole diameter $a = 2.5$ mm. Calculated profile of the zoned metalens (black line) along with the non-zoned profile (blue line), successive steps (light-blue lines) and thickness limit (red-dashed line) for the cases with $q = 0$ (b) and $q = 1$ (c).

with a $FL = 4.5\lambda_0$ [14], [15]. At this frequency, the effective refractive index of the fishnet metamaterial is near zero with $n_{lens} = -0.25$. By applying (1) along with the thickness limit (t_{total}), the profiles of the four fishnet metalenses are obtained for different values of reference phase. For example, the designed profiles for the case $q = 0$ and $q = 1$ (i.e., a reference phase of 0 and 2π) are shown in Fig. (b) and (c), respectively, along with the curves corresponding to the non-zoned profile, successive steps and thickness limit. It can be clearly observed how an introduction of a reference phase is directly translated into an increase of the first zone (and also of the following zones) along both x and z axes. Hence, the volume of the zoned lens is increased, as expected.

To evaluate the focusing performance of the metalenses, the commercial Software CST Microwave StudioTM was used with the setup described in [14], [16], [18]. The metalenses were designed with a line focus and a full ‘building block’ of perforated plate with a matrix of 37×23 subwavelength holes along x and y axes. This yields total lateral dimensions of $21\lambda_0 \times 21.73\lambda_0$ (111 mm \times 115 mm) along x and y axes, respectively. The total dimensions of the metalenses were designed following the -12dB edge taper criterion in order to reduce

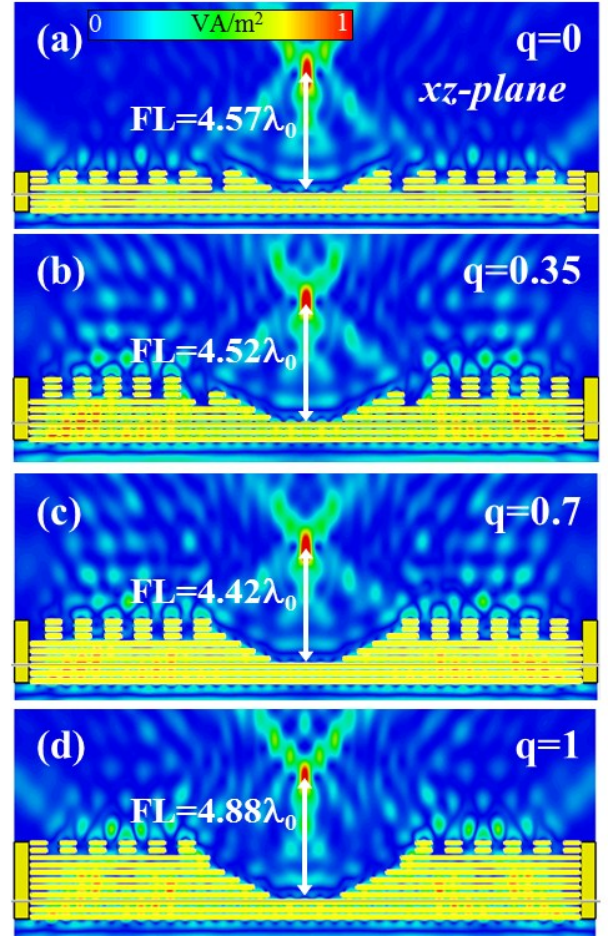


Fig.2 Numerical results of the normalized power distribution on the $xz(H)$ -plane for the metalenses with $q = 0$ (a), $q = 0.35$ (b), $q = 0.7$ (c) and $q = 1$ (d).

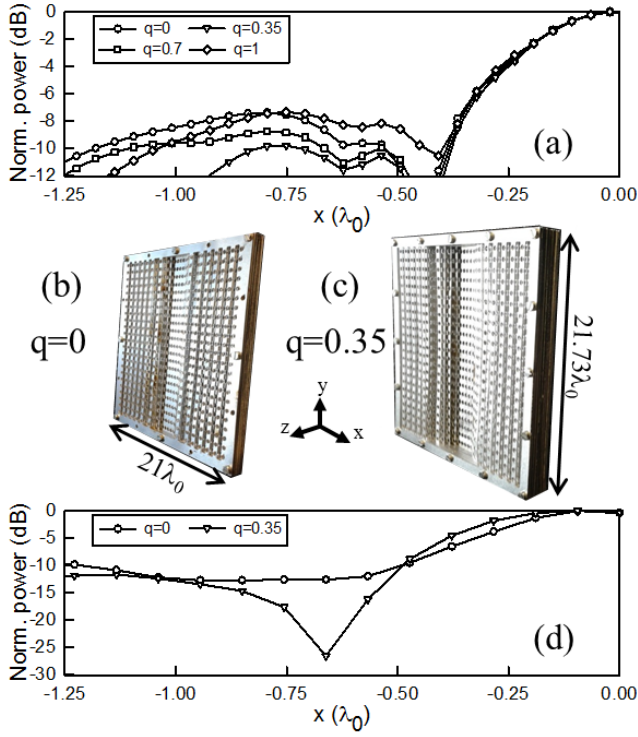


Fig.3 (a) Numerical results of the normalized power distribution along the transversal x -axis for the different cases of reference phase here studied. Fabricated cylindrical plano-concave zoned fishnet metalenses with values of $q = 0$ (b) and $q = 0.35$ (c): i.e., the cases without and with reference phase, respectively. (d) Experimental results of the normalized power distribution along the transversal x -axis for both designs.

spill over [20] taking into account the radiation pattern of an open ended rectangular waveguide (used as a transmitter when using the metalenses as lens-antennas). Finally, the metalenses were illuminated from their flat face with a vertically polarized planewave (E_y).

The numerical results of the normalized power distribution on the xz -plane for the four considered metalenses here designed are shown in Fig. 2 at the designed frequency $f = 56.7$ GHz ($\lambda_0 = 5.29$ mm). From these results, it can be observed that focusing is achieved for all the metalenses. Moreover, the increase of the first zone (and also the other zones) due to the reference phase is more evident by looking at their profiles. Regarding the FL , it is shown that it is closer to the designed value for the case with $q = 0.35$ (a reference phase of 0.7π) with a small deviation of 0.44%. Moreover, the power at the FL is higher for this design compared with the other cases (not shown here) [18]. Also, the numerical results of the power distribution along the transversal x -axis for all considered metalenses at each FL are shown in Fig. 3(a). From these results, it can be observed that the SLL is clearly reduced for the cases with $q = 0.35$ and $q = 0.7$ while it is almost identical for the cases with $q = 0$ and $q = 1$. The best performance is obtained for the design with $q = 0.35$ with a SLL of 9.7 dB (which represents a reduction of SLL of 2.2 dB compared with the case without reference phase). Moreover, the lowest first null magnitude is obtained with this design with a value of 17 dB.

In light of the previous results, two prototypes were fabricated in order to evaluate the metalenses experimentally: without ($q = 0$) and with ($q = 0.35$) reference phase. The corresponding pictures are shown in Fig. 3(b) and (c), respectively. To same experimental setup as in our previous works was used [14], [16]. First, the experimental FL was measured at the design frequency and the values are $4.2\lambda_0$ and $4.1\lambda_0$ for the case with ($q = 0.35$) and without ($q = 0$) reference phase, respectively. Moreover, the experimental results of the normalized power distribution along the transversal x -axis for both metalenses at each experimental FL are shown in Fig. 3(d). It can be observed that a clear reduction of the SLL is achieved for the design with $q = 0.35$ with a value of 12.5dB while it is 10 dB for the case without reference phase ($q = 0$). Also, the first null is reduced ~ 12 dB for the case with reference phase, demonstrating a good agreement with the numerical results. The differences with the numerical results are attributed to the fact that the detector (open ended rectangular waveguide) has not been de-embedded from the measurements. Also, one cannot rule out some errors in the fabrication process.

Finally, these metalenses were evaluated as a lens-antenna system (not shown here) by illuminating the metalenses from their profiled face using an open ended rectangular waveguide at each experimental FL . Experimental results demonstrate that a reduction of side-lobes in the farfield of 2.4 dB is achieved for the case with reference phase. Moreover, the experimental gain obtained for the case with $q = 0.35$ is 11.3 dB while it is 9.53 dB for the case of $q = 0$, in good agreement with the numerical results.

III. CONCLUSIONS

In this communication, the recently proposed reference phase has been applied in the design of zoned fishnet metalenses with the aim to reduce the SLL and first null. The design approach has been presented and four metalenses have been designed at $f = 56.7$ GHz with a $FL = 4.5\lambda_0$ using different values of reference phase. The numerical results of the power distribution along the optical z -axis and the transversal x -axis demonstrate that the best performance of the focus is obtained for the case with $q = 0.35$ (reference phase of 0.7π) in terms of the FL , side lobe reduction and first null. Hence, two prototypes were fabricated to evaluate their performance: with ($q = 0.35$) and without ($q = 0$) reference phase. The experimental results of the normalized power distribution along the transversal x -axis at each experimental FL demonstrate that the SLL is reduced up to 2.5 dB when a reference phase is introduced. Also, a clear reduction of the first null is obtained for this design. When the metalenses are used as lens-antenna systems, a reduction of SLL is also achieved in the farfield and the experimental gain for the case of $q = 0.35$ is 1.77 dB higher than the case without reference phase, demonstrating a good agreement with numerical calculations. The results here presented may be used to improve the performance of a lens antenna system by designing zoned lenses made of different materials.

ACKNOWLEDGMENT

This work was supported by the Spanish Government under contract TEC2014-51902-C2-2-R. V.P.-P. is sponsored by Spanish Ministerio de Educación, Cultura y Deporte under grant FPU AP-2012-3796. B. O. is sponsored by Spanish MINECO under grant FPI BES-2012-054909. M. N.-C. is supported by the Birmingham Fellowship. M.B. is sponsored by the Spanish Government via RYC-2011-08221.

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